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A Brief History of Laser AGEX

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A great deal of physics understanding is required for the design and construction of thermonuclear weapons. Since the days of the Manhattan Project, physicists have relied on a combination of theory and experiment for the successful creation of nuclear weapons. One of the great experimental difficulties faced by the designers of nuclear weapons is that nuclear weapons operate in a high energy density regime not found on the earth except during a nuclear weapon detonation. Replicating these conditions is difficult unless a nuclear weapon is actually detonated. One of the reasons for the large number of expensive tests at the Nevada Test Site was that there was no other way to obtain the required data.

When the laser was first developed many in the weapons program realized that the ability of a laser to concentrate a large amount of energy in a small volume could create experimental conditions that would be useful for studying the physics of nuclear weapons. The national weapons labs began investigating this possibility and started building ever bigger and better lasers. The vast difference in energy scales between the laboratory and a nuclear weapons explosion meant large and powerful lasers were required. By the early '80's concrete plans for the use of lasers in weapon physics experiments were beginning to be proposed. One of the earliest was the "Proposals for Laboratory Weapon Physics Experiments" in 1982 put out by the Physics Experiments Advisory Panel.[1] The radiation hydrodynamics experiments described in these early proposals formed the basis for many of the experiments on lasers that have performed for the last two decades.

The Nova laser, which operated between 1984 and 1998 successfully, showed that many of these proposals could be carried out on a large laser system. One of the earliest experiments on Nova was in the area of x-ray opacity. Materials vary in the degree to which they absorb and re-emit radiation of given wavelengths under given conditions, directly affecting the passage of radiation through them. Because x-rays transport much of the energy in a nuclear weapon, weapon physics is concerned particularly with opacities at x-ray wavelengths.

In the high-temperature plasmas created by nuclear detonation, atoms become highly ionized and the number of possible atomic transitions grows very large. The complicated interaction of radiation with these complex ions makes opacity hard to calculate and forces scientists to rely on approximations. To test such approximations, they conducted experiments on the Nova laser on many different materials at various temperatures and densities. Comparison of these data with code calculations was then used to improve both physical models and computer simulations of opacity. Because opacity varies rapidly with sample conditions, experiments demanded accurate measurement not only of opacity but also of temperature and density. This required that the sample's temperature and density is spatially uniform. On Nova weapon scientists devised techniques for doing so within laser-produced plasmas.

In a typical experiment, an opacity sample doped with a tracer material with a low atomic number (e.g., aluminum) is sandwiched between layers of plastic and put into a hohlraum. Laser-generated x rays heat and ionize the sample. Constrained by the plastic, the sample expands uniformly and so maintains a constant density. X-ray backlighting, produced by separate laser beams hitting small fibers, probes the target to provide the required measurements. Two x-ray backlight sources are used. X-rays from one backlighter pass through the sample to a x-ray spectrometer, which measures the transmitted spectrum to give the opacity. An experimental setup is shown schematically in Figure 1. The spectrometer also records the absorption spectrum of the tracer material.

From the degree of tracer ionization, the sample's temperature can be determined to better than 5% accuracy. The other backlighter illuminates the sample from the side, allowing the width of the expanding sample to be measured and its density to be computed. Figure 2 compares opacity data obtained with the Nova laser with results obtained using an opacity code developed at LLNL.

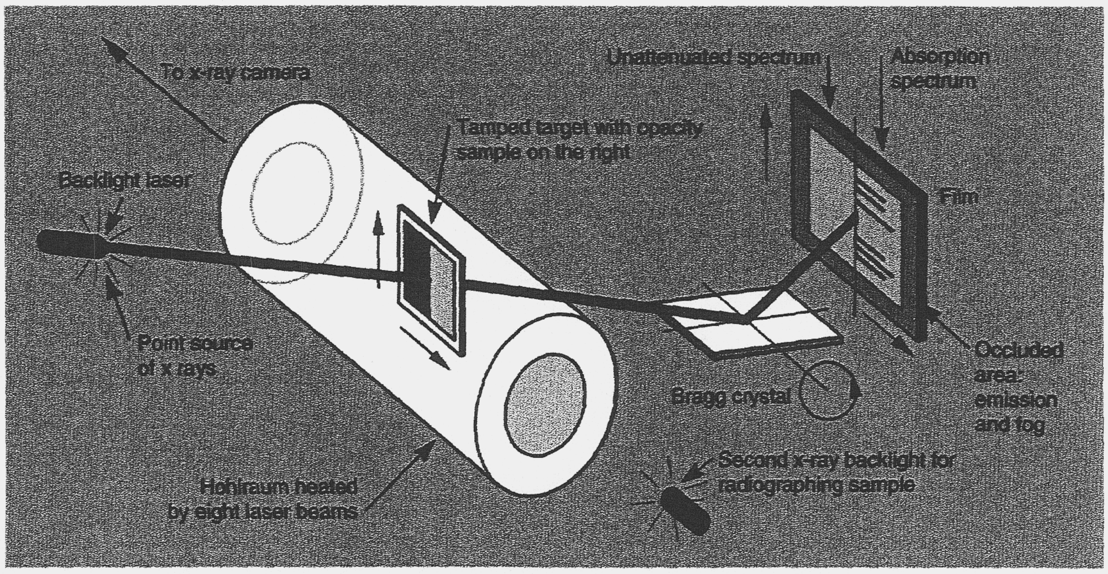


Figure 1. Schematic of point projection spectroscopy for opacity measurements. The laser-produced backlight x rays are imaged after passing through the target. The image is spatially and spectrally resolved by a Bragg crystal, while temporal resolution is provided by backlight duration.

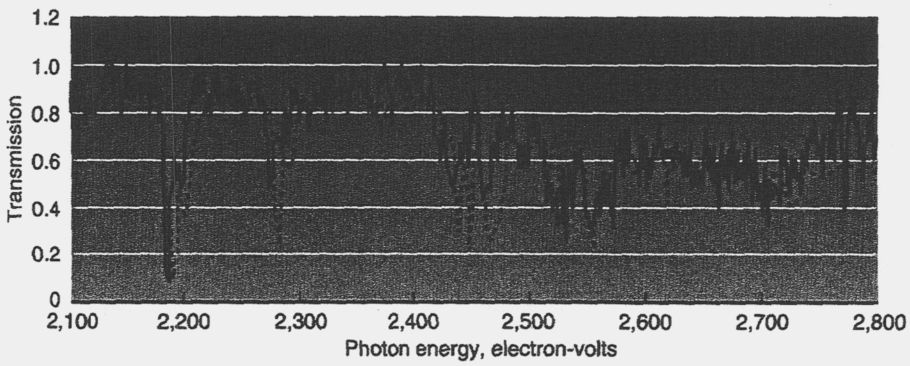


Figure 2. Experimental opacity data compared with calculations. The solid line shows measured x-ray transmission through a niobium sample. The dashed line shows the similar results calculated using an opacity code developed at LLNL. Good agreement with experimental data bolsters confidence in the opacity calculations and their underlying theory.

Another early experiment performed on Nova investigated the physics of turbulent mixing in plasmas. In contrast to the smooth, orderly behavior of fluids in laminar flow, rapidly moving fluids tend to become turbulent. Turbulence in swiftly flowing fluids promotes their mixing, such as where fluids of different density border each other. Scientists study three types of turbulent mixing observed in nuclear weapons: acceleration-induced, when a lighter fluid pushes against a denser fluid (known as the Rayleigh-Taylor instability); shock-induced, when a shock wave passes through the fluid interface (Richtmyer-Meshkov instability); and shear-induced, when two fluids in contact are moving relative to each other (Kelvin- Helmholtz instability). Turbulent mixing is a factor in understanding the operation of both the primaries and secondaries of nuclear weapons. Experiments on Nova also began to measure the growth of the Rayleigh-Taylor instability in solids. Mounted in a hohlraum, a foil of copper or molybdenum is compressed and shocked while maintained below its melting point. Only after the drive ceases and the metal decompresses does the foil melt, and only then does Rayleigh-Taylor instability appear to develop normally. In other words, the strength of the compressed metal stabilizes the interface. These experiments are directly relevant to primaries, where materials retain strength throughout much of the explosion.

In the familiar low-energy-density world, most fluid flows behave as if incompressible. But weapon physics must deal with the compressible flows that exist under conditions of high energy-density. Understanding the effects of compressibility and radiation flow on hydrodynamic mixing is crucial. Compressibility alters density, affecting the evolution of perturbations and the behavior of mixing. One Nova experiment investigated turbulent mixing caused by shock-induced Richtmyer-Meshkov instabilities in an environment of high energy-density. The experimental package comprised a beryllium tube mounted perpendicularly to the side of a standard Nova hohlraum (Figure 3). Within the tube nearest the hohlraum was a plastic section, beyond which was a cylinder of low-density foam. Rapidly heated to very high temperature by the focused laser beams, the hohlraum launched a shock into the plastic. Upon crossing the sawtooth-shaped interface between plastic and foam, the shock induced a mixing flow (Figure 4a). Experimental results agreed well both with simulations and a theoretical model (Figure 4b).

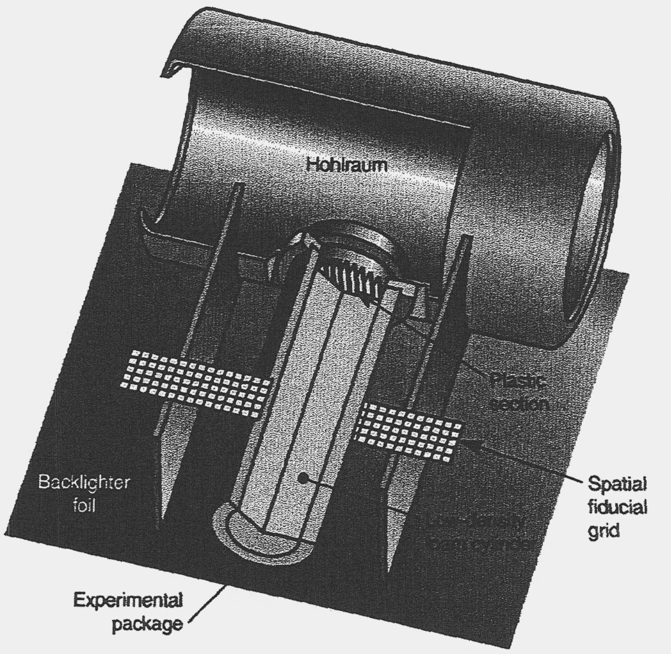
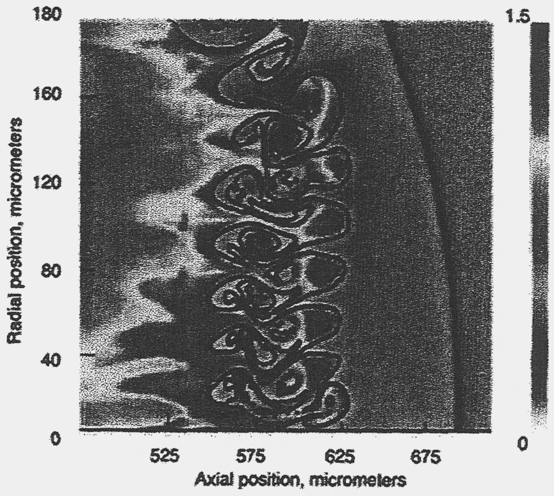


Figure 3. Cutaway view of the hohlraum and attached experimental package for measuring shock-induced mixing. Within the beryllium shock tube is the plastic section with machined sawtoothed perturbations and the low-density foam cylinder. Behind the experimental package is the backlighter foil.

(a)



(b)

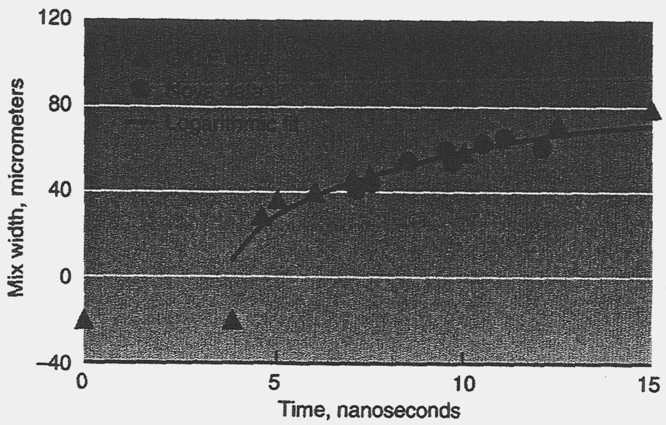


Figure 4. (a) Mixing flow showing density and material contours 7.5 nanoseconds after shock delivery, as model by the two-dimensional CALE computer code. (The bar to the right is the logarithm of density.) (b) The width of the mixing region evolves logarithmically with time. The circle represent measured widths from Nova experiments; the triangles represent data points calculated using the CALE code. Good agreement between experimental data and numerical simulation promotes confidence in the code.

Other Nova experiments were designed to investigate the limits of two-dimensional hydrodynamics codes. The advent of hydrodynamics codes that could do three-dimensional calculations was the driving force behind these experiments. In principle, a three-dimensional code should do a better job of simulating experiments than a two-dimensional calculation, but it is essential to verify the code by comparing it to actual experiments. Figure 5 compares three-dimensional surface plots created from data from one Nova experiment with a three-dimensional simulation of the event created by the HYDRA three-dimensional simulation code. Both representations show a broad bubble surrounding narrow spikes, a shape characteristic of the nonlinear phase of the Rayleigh- Taylor instability. The HYDRA simulation reproduces not only the overall magnitude of the perturbation, but essentially all of the details of the shape, and demonstrates the ability to accurately model in three dimensions nonlinear aspects of high-energy-density experiments

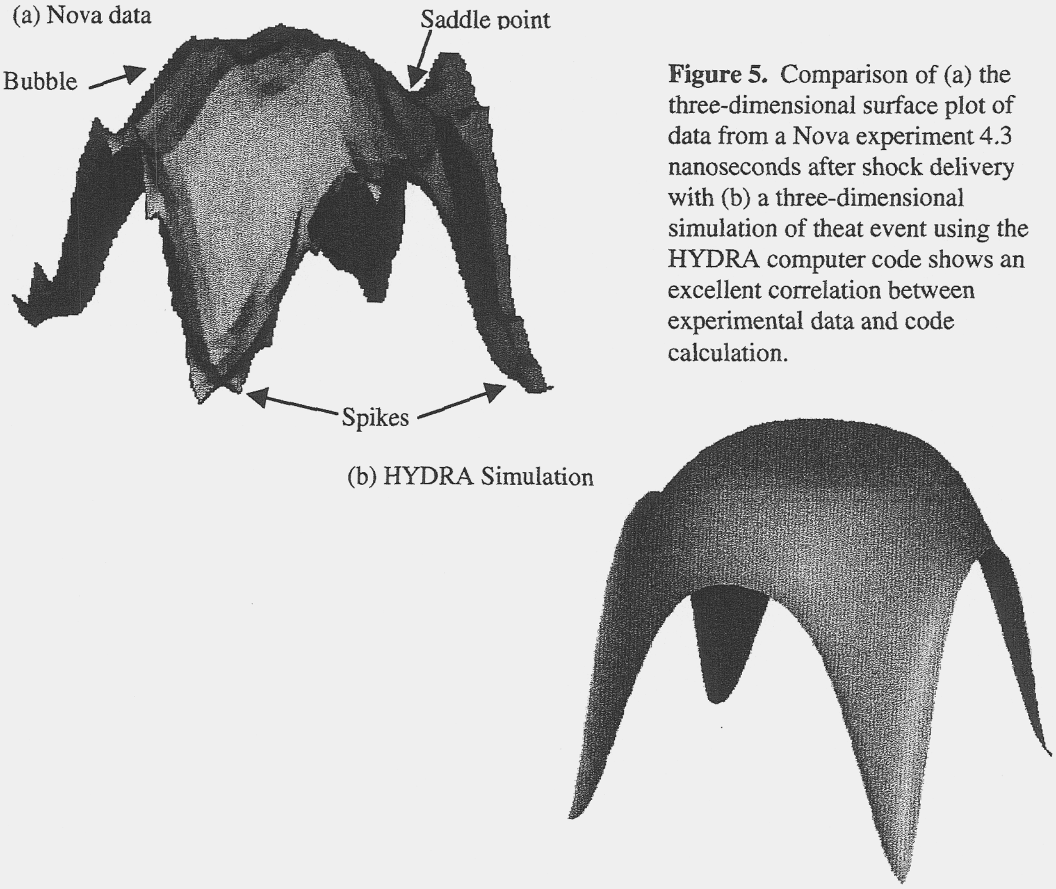


Figure 5. Comparison of (a) the three-dimensional surface plot of data from a Nova experiment 4.3 nanoseconds after shock delivery with (b) a three-dimensional simulation of theat event using the HYDRA computer code shows an excellent correlation between experimental data and code calculation.

Another use of Nova was to measure the equation of state of many materials. The equation of state mathematically expresses the thermodynamic relationship between the energy content of a mass of material, its volume, and its temperature. High-energy-density equations of state are fundamental in describing such phenomena as hydrodynamics and radiation transport; their fundamental importance also makes them crucial in understanding the operation of nuclear weapons. Shock compression is a widely used method for experimentally determining equations of state at high pressures. An experiment begins with determining the initial pressure, volume, and energy of the material. Compressed by a single shock wave to greater pressure, the material's volume changes to a new state at higher density, temperature, and pressure. By varying the shock strength in a series of experiments from the same starting conditions, scientists can obtain a set of pressure-volume pairs. They can then plot these pairs to produce the material's Hugoniot--that is, the mathematical curve relating the velocity of a single shock wave to the pressure, density, and total heat of the transmitting material before and after the shock wave passes. Because of its relative simplicity, the Hugoniot is the primary avenue for investigating a material's equation of state experimentally.

Each material possesses its own unique equation of state. No single valid model exists for the entire range of variables, which may cover many orders of magnitude in nuclear weapons operations. Thus, the equation of state for a particular material derives from models of limited scope for particular regimes of pressure, density, and temperature. These models are usually collected in a table of equation-of-state values that can be used in code calculations. For nuclear detonations, the equation of state extends through two distinct regimes. In the early phase of implosion, before any significant nuclear yield, temperatures are relatively low and such factors as strength of material and chemical reaction are most significant. Scientists study this relatively low-energy-density regime through experiments using high explosives or gas guns, which in high-density materials can generate pressures up to a few megabars--that is, up to a few million times normal atmospheric pressure. Such data determine the lower end of the curve in Figure 6, which shows the Hugoniot of aluminum.

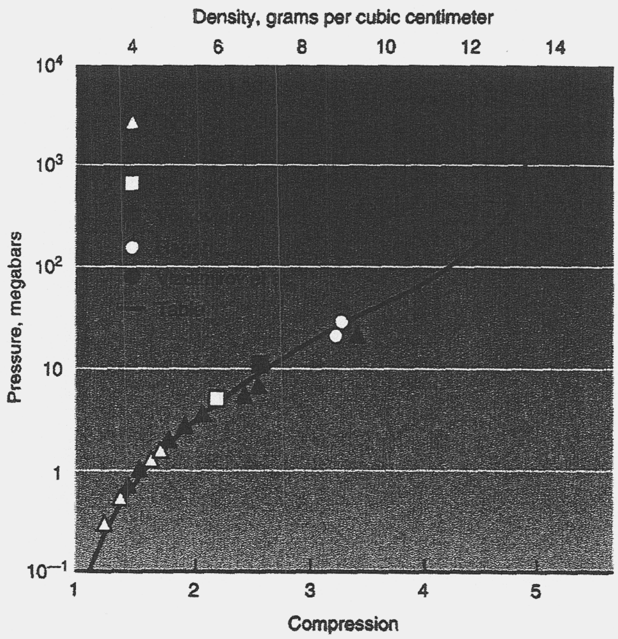


Figure 6. Comparison of experimental and theoretical shock Hugoniots of aluminum. The data points at the upper, highest pressure portion of the graph come from experiments conducted in Soviet nuclear weapons tests and reported in the open literature.

Vastly higher pressures, hundreds of megabars, characterize high-energy-density regimes, where prior to laser experiments data could only be acquired through nuclear tests. Data points at the upper end of the curve in Figure 6 come, with large uncertainties, from openly published work based on the Soviet underground nuclear test program. Because of insufficient experimental data, scientists must interpolate the intermediate portion of the curve and extrapolate to pressures beyond the data. At multi-megabar pressures, neighboring atoms are packed so tightly as to disrupt each other's outermost electron shells. The resulting ionization caused by pressure absorbs large amounts of energy and makes the material more compressible. Various theories predict different curves, as Figure 7 illustrates for aluminum. Potentially, powerful lasers can provide experimental data to fill in the curve, not only for aluminum but for many other materials.

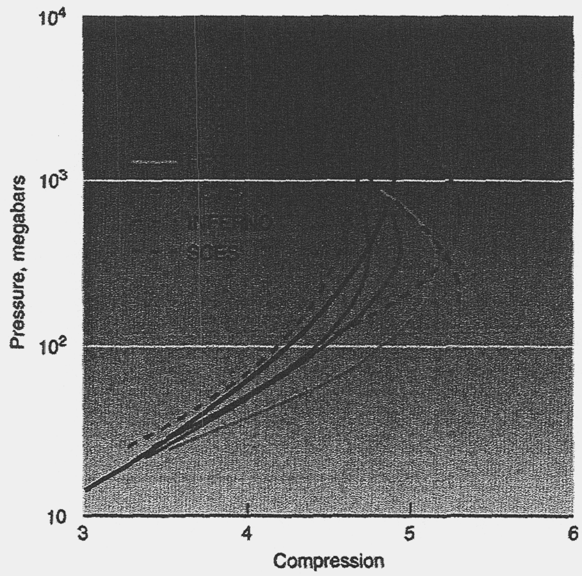


Figure 7. Calculations of the principal Hugoniot of aluminum using a variety of theoretical methods, plotted for high pressure and compression, where the various models exhibit differences: Thomas-Fermi model with quantum corrections (TFQC), semi-classical equation of state (SCES), self-consistent field (SCF), Hartree-Fock-Slater (HFS), ionization equilibrium plasma (ACTEX), INFERNO, and another version of the semi-classical equation of state (SCES').

For each point on the Hugoniot, scientists must measure two quantities. One is usually the speed of the shock in the material. Another can be the speed to which the shocked material has been accelerated, the so-called particle speed. To measure shock-wave and particle speeds, scientists use x-ray backlighting. A shock can be driven into a material with a laser. A beam of x rays generated by a second laser with well-known and closely controlled characteristics illuminates the target from the side. Material changes caused by the shock wave absorb the x-ray backlight differently as it passes through the target. Captured on film, these differences provide the data required to compute points on the Hugoniot. To measure the principal Hugoniot, the target material at standard temperature and pressure is struck with single shocks of different strength. Measuring the thermodynamic states created when single shock waves pass through the target material gives scientists a set of data points that lie on the principal Hugoniot, which they can then plot. Figure 8 illustrates a recent Nova experiment to measure thermodynamic states.

The target had two parts: a flat, very thin plastic "piston" and a wafer of the compound under study. Laser-generated x rays launched a strong shock, several tens of megabars, into the piston, sending a shock wave through the wafer.

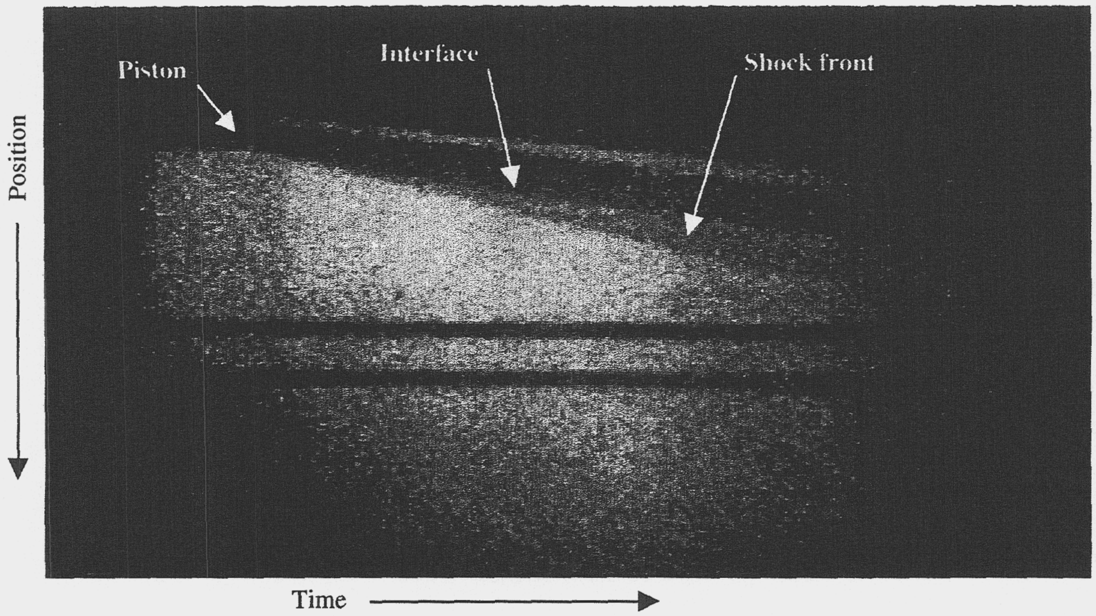


Figure 8. Initial results from an experiment using the Nova laser to measure the equation of state of a plastic. The time-resolved one-dimensional image shows the interface between a plastic piston (doped with bromine to make it opaque to the x-ray backlighter) and the undoped plastic sample being compressed. Note the shock front moving ahead in the plastic.

Another measurement technique, impedance matching or shock breakout, relies on comparing shock velocities in a reference material of known characteristics (often aluminum) with those in a test sample. Laser-generated x rays or a laser-accelerated flyer plate shocks the target, which comprises precisely measured thicknesses (called steps) of the test sample alongside reference material. Diagnostic instruments record the time it takes the shock wave to break through the opposite faces of the steps, thereby determining the shock speed in both materials. Comparing the test sample with the known standard yieldsinformation on the equation of state of the sample. Uncertainties in important details can complicate interpretation of the results of equation-of-state experiments. Was an absolutely planar shock delivered to the target? Could electrons or radiation from the hohlraum have affected the target before the shock arrived? Despite such challenges, lasers offer the only path currently available for such investigations at pressures greater than 10 megabars, where many theoretical uncertainties linger.

In addition to studying individual physical processes such as opacity, hydrodynamic mixing, and equation of state, other experiments on Nova were designed to be so complex that they must be modeled with computer codes that take into account the full range of hydrodynamic and radiative processes that would formerly have been involved in a nuclear test. These so-called integrated experiments are intended to validate the integrated physical models and to test the scientist's ability to model extremely complex behavior. While most proposals for these types of experiments require most energy than could be delivered on Nova still preliminary experiments on Nova helped to develop research techniques and increase the physics understanding of these experiments.

In one type of radiation hydrodynamics experiment, a thin opaque foil replaced part of the hohlraum wall. Laser-generated x rays inside the hohlraum blew off the foil's inside surface, driving a shock back into the foil. The shock traversed the foil and broke out its back surface. An ultraviolet telescope, coupled with an optical streak camera, was focused on the foil's back side to measure the time of shock breakout, from which the temperature inside the hohlraum could be inferred.

The radiation field inside the hohlraum also drove a radiative heat wave through the shocked foil material. The breakout of this heat wave on the foil's back side was recorded by a streak camera. By using different types and thicknesses of foils, scientists attempted to understand the different effects of opacity, temperature drive, and radiative heat transport.

In a similar type of experiment, a thick sample of low-density foam replaced the thin foil. At low enough densities, the heat front preceded the shock front, permitting scientists to study heat transport through unshocked material. This type of experiment also allows viewing the sample from the side; x-ray backlighting techniques allow the shock position through the sample to be measured as a function of time. This technique gives a great deal more information than the simple shock breakout experiment.

When Nova ceased operations in 1998 weapon scientists doing experiments on lasers moved their experiments to the Omega laser. The Omega laser has essentially the same energy and power as did the Nova laser but it has sixty beams instead of ten beams. High energy density experiments have taken advantage of this feature to extend and improve on the experiments performed at Nova, but the classes of experiments have not changed.

Several radiation hydrodynamics experiments have been performed. In one the shock tube arrangement shown in Figure 3 was modified so that shocks could be driven in from both ends of the tube as shown in Figure 9. Previous shock-tube experiments on double-shocked mixing layers indicated that the growth rate of the mixing region is greatly enhanced upon passage of the second shock, showing a rapid transition to turbulence. Laser beams entering each hohlraum produce x-rays which heat the plastic ablators. On one side the x-rays ablatively launch a shock of approximately Mach 20 into a carbon-foam-filled Be-lined miniature shock tube and across an interface. A second, counterpropagating shock is launched from the opposite end of the shock tube by a second half-hohlraum driver; the second shock strikes the interface region later than the first. By placing initial perturbations on the interface, the effect of the second-shock on the growth of the Richtmyer-Meshkov instability can be measured. In addition, by delaying the laser beams entering the second half-hohlraum driver, the relative timing of the second shock arrival can be arbitrarily controlled.

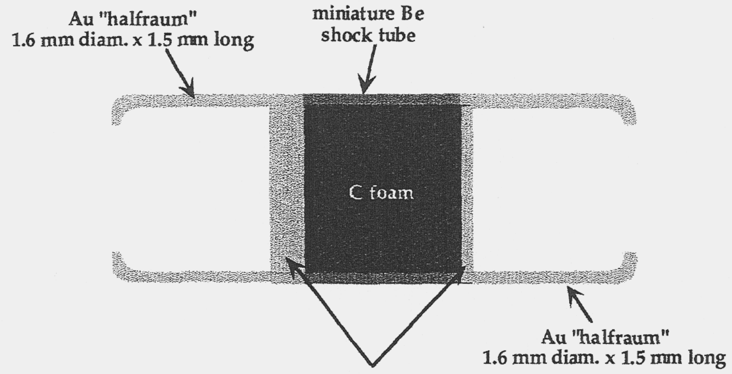


Figure 9. Geometry for double-shocked experiments.

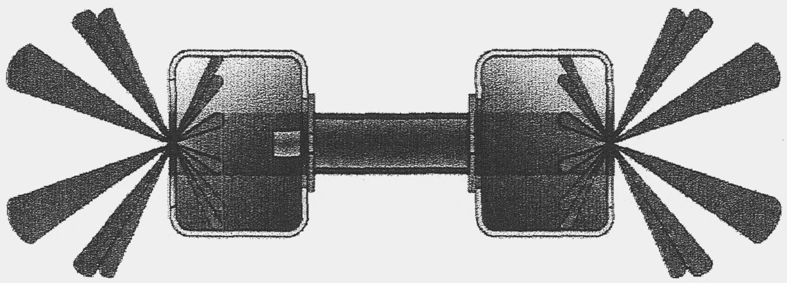


Figure 10. Geometry for interacting jet experiments.

In a variant of this experiment shown in Figure 10, the half hohraum on the right is used to launch a planar shock which collides with a supersonic jet produced by the hohlraum on the left. The jet is produced by x-ray ablation of the surface of the small aluminum cylinder placed in the inside end of the half hohlraum. The resulting shocks propagate radially to the axis of the cylinder where they collide producing the supersonic jet. In order to achieve the desired convergence, placement of the laser beams had to be very precisely controlled. In these experiments 35 laser beams were pointed to 27 distinct locations as is shown in Figure 11. Also in the figure are three pieces of data showing the collision of the jet with the counterpropagating shock.

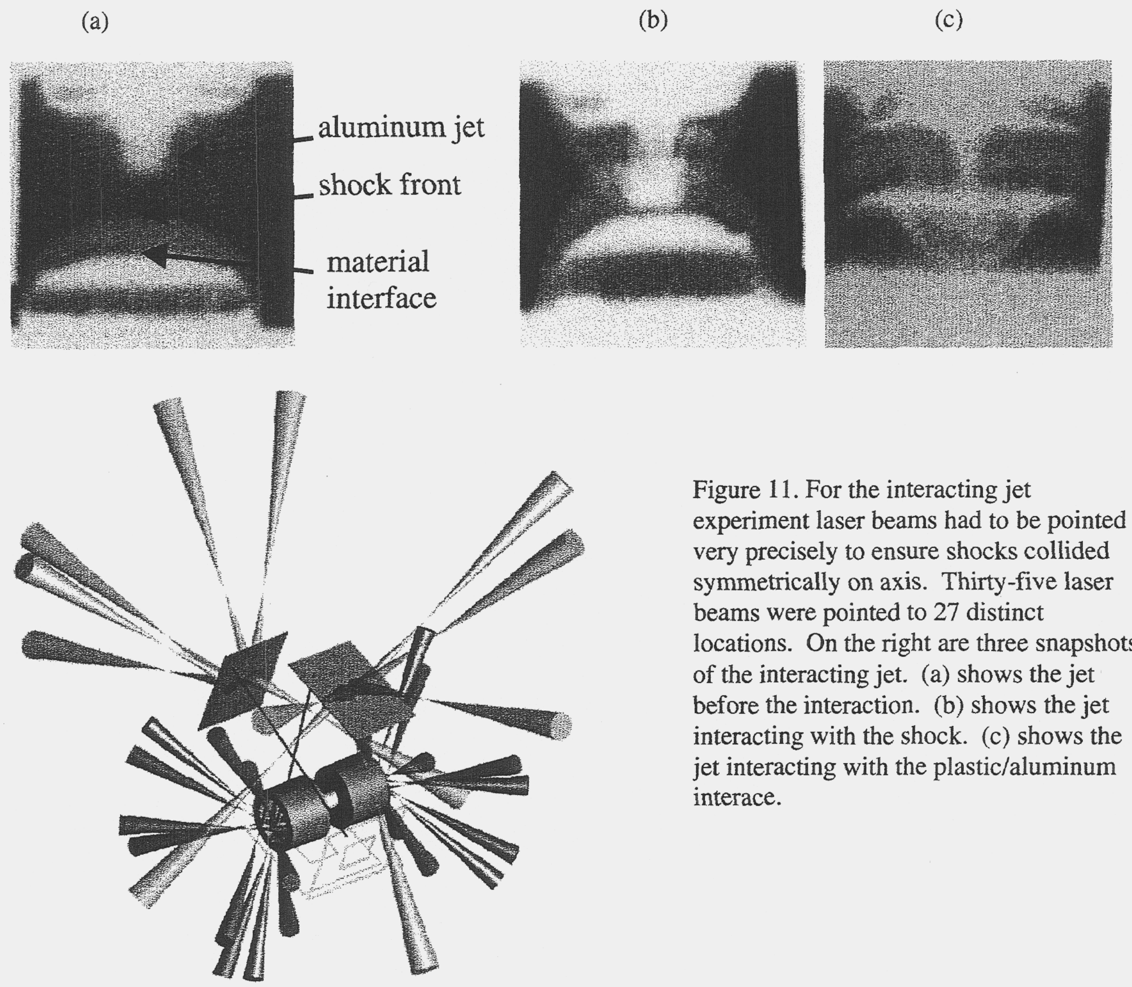
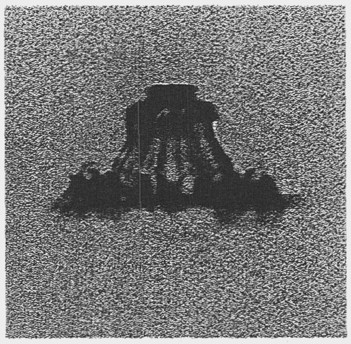


Figure 11. For the interacting jet experiment laser beams had to be pointed very precisely to ensure shocks collided symmetrically on axis. Thirty-five laser beams were pointed to 27 distinct locations. On the right are three snapshots of the interacting jet. (a) shows the jet before the interaction. (b) shows the jet interacting with the shock. (c) shows the jet interacting with the plastic/aluminum interace.

Another experiment carried out in shock tube attempts to measure the transition from 2D to 3D in a geometry that starts out with 2D symmetry. This experiment will be compared with 3D code modeling to verify the new generation of 3D codes being developed. The geometry is similar to Figure 3 except a spherical cooper ball is placed in the center of the attached cylinder. A shock of Mach ~10 to 20, created by a 1-ns laser pulse into the main hohlraum, propagates down the foam-filled Be shock tube and interacts with the spherical cooper ball placed downstream. This problem, initially 2D-axisymmetric, becomes 3D at latetimes when an azimuthal-bending mode instability (theWidnall instability) begins to develop at the back end of the crushed sphere. This 2D-to-3D transition is qualitatively predicted by 3D codes (Figure 12a) and not predicted by 2D codes (Figure 12b). X-ray radiographs are taken of the Cu sphere, and a central void within the sphere (illustrated in Figure 12c) is measured, characteristic of the 3D fingering signaling the 2D-to-3D transition.

(a)



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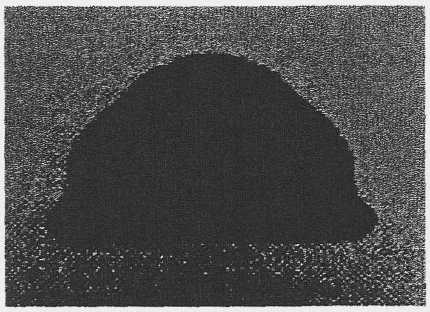
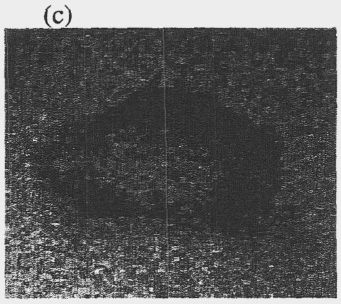


(c)



On Omega the radiation flow experiments that were started on Nova have moved to ever increasingly complex geometries. Recent experiments investigated the importance of high-Z walls in determining the radiation transport in low density foams. The samples consisted of 40-mg/cm^3, Ta_2O_5 foam cylinders. The foam faces were irradiated from one end by a soft x-ray drive, designed to provide supersonic radiation flow. An example of radially resolved, streaked radiation breakout data is shown in Figure 13. The data shows that the radiation wave takes about s1 ns longer to burn through at the edges of a foam than at the center, demonstrating the importance of wall losses in Nova-and-OMEGA-scale radiation-flow experiments. Simple analytic models developed this year confirm this significant radiation-front curvature. Comparisons between measured and predicted breakout times at the center of the foam plotted in Figure 14 show extremely good agreement.

The preceding list of experiments that have performed on the Nova and Omega lasers is only a sampling. The experiments are, however, fairly representative of the experiments that have been performed. They have laid the groundwork for experiments that will be performed on the NIF. The use of lasers to provide data useful to the weapons program has been demonstrated and the increased energy of the NIF will allow a great improvement in the kind and quality of experiments that can be performed.

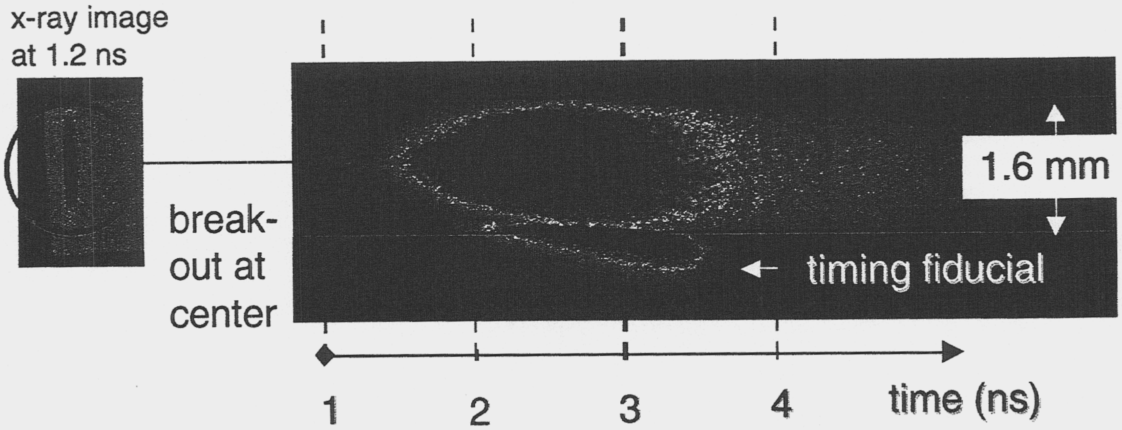


Figure 13. Radially resolved, temporally streaked image of radiation breakout from low density foam.

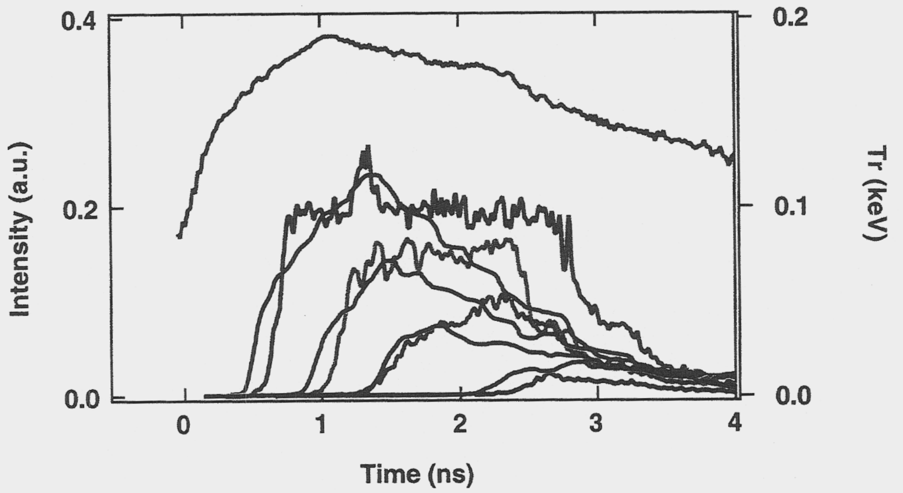


Figure 14. Temporal intensity versus time at foam center for four different lengths of foam. The lengths were .25 mm, .50 mm, .75 mm, and 1.00 mm. Radiation breaks out at successively later times as the length is increased. Dashed lines show data; solid lines show calculations. The measured radiation drive temperature (top curve) is plotted along the right-hand axis.

References

1. C. T. Alonso, Chairman. "Proposals for Laboratory Weapon Physics Experiments," Physics Experiments Advisory Panel, LLNL, Vol. I and II, UCRL-53293 (1982).